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Research paper

Spatial apportionment of urban greenhouse gas emission inventory and its implications for urban planning: A case study of Xiamen, China

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ABSTRACT

Cities have become a major source of greenhouse gas (GHG) emissions and controlling urban GHG emissions is a critical response to global climate change. Many previous studies on urban GHG emissions focused on inventories, changes and impact factors but few investigated the distribution of spatial sources within a city. Although inventories of a city can give information of GHG emissions from different sectors, urban government and planners need to know where emissions occur and how (or why) they occur where they do. It is thus important to spatially apportion GHG emission within a city for the practical application of GHG emission management and policies. In this study, we develop a framework for the spatial apportionment of urban GHG emissions. Xiamen is taken as a typical rapidly urbanizing city in China to demonstrate the framework of spatial apportionment. Results show that the ranking of GHG emission intensity for different land-use types of the city is manufacturing, mining, warehouse land, service industry land, transportation land, residential land and agriculture land with a ratio of 89:54:23:14:1. The vast majority of land for GHG sequestration was located in the peripheral area of the city and most land-use types in the central region of Xiamen had high GHG emissions. The implication for low-carbon urban planning is then discussed in terms of structure and connection strategies. Integrated with socioeconomic factors and urban land-use distribution, the spatial apportionment of GHG emission inventory can provide a more accurate analysis of emission sources and better management of emission sources through urban planning.

1. Introduction

Cities have become important sources of greenhouse gas (GHG) emissions and the control of urban GHG emissions is the main task in coping with global climate change at present (Bai, 2007; Kennedy et al., 2010; Potere and Schneider, 2007). As inventorying GHG emissions is the first step to addressing climate change, many cities have compiled a GHG emission inventory according to guidelines proposed by international organizations or their national governments (Baldasano et al., 1999; Borin et al., 2009; Brady and Fath, 2008; Carlson et al., 2014; Chow et al., 2011; Dickinson and Desai, 2007; Kennedy et al., 2010; Kling, 2008; Mitchell, 2012). An inventory of GHG emissions can help a city clarify the structure and quantity of GHG emissions and then take mitigation actions for specific sectors such as residential, industry and transportation sectors. However, residents, enterprises and other institutes within the city are the eventual implementers of GHG emission mitigation actions planned for different sectors. Urban government and planners also need information on where GHG emissions occur and why they occur where they do. So the importance of spatial apportionment of urban greenhouse gas emission inventory lies in the following reasons:

Firstly, the scaling down of the GHG inventory through spatial apportionment will provide detailed information for emission management and decision support. Integrated with socioeconomic factors and the urban land-use distribution, the spatial source apportionment of GHG emissions can allow a more accurate analysis for the control and management of emission sources. It is thus necessary to spatially apportion sources of GHG emissions within a city. Meanwhile, the consensus of urban planners is to consider climate factors in urban planning and to combine GHG emission accounting with urban planning, which requires the spatial apportionment of the GHG emission inventory.

Previous research has mainly focused on the development of a GHG emission inventory and the dynamics of GHG emissions and their driving forces, with few works addressing the spatial apportionment of the emission inventory (Christen, 2014; Dodman, 2009; Hoornweg et al., 2011; Kennedy et al., 2009; Kennedy et al., 2010; Satterthwaite, 2008). In addition, studies have mainly been conducted for the whole

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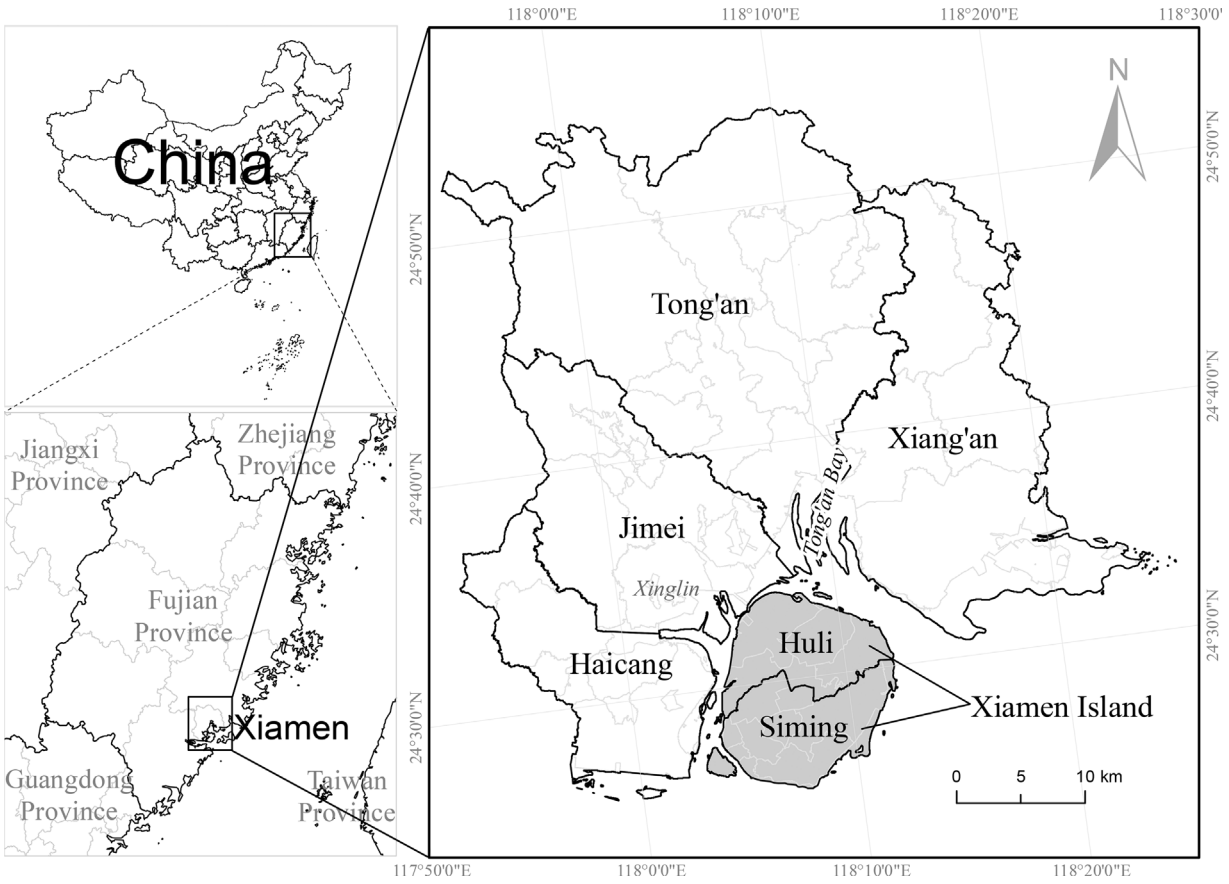

Fig. 1. Location of Xiamen.

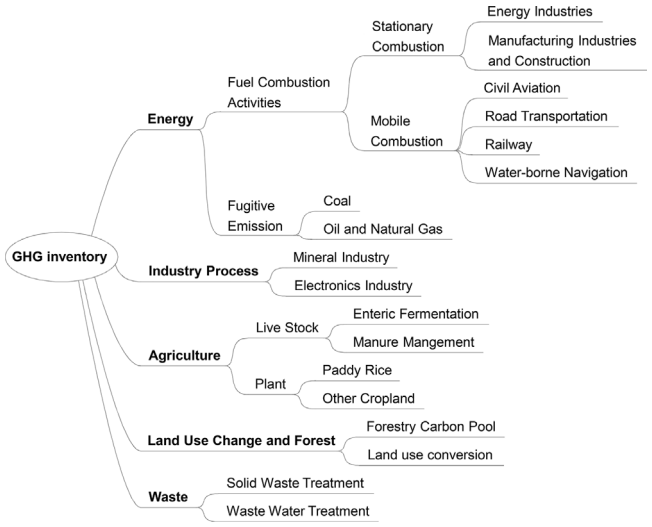

Fig. 2. Scope of GHG inventory.

Table 1
Global Warming Potential (GWP) of the assessed gases.

Gas	GWP	Gas	GWP
CO_2	1	HFC-143a	3800
CH_4	21	HFC-152a	140
N_2O	310	HFC-227ea	2900
HFC-23	11700	HFC-236fa	6300
HFC-32	650	CF_4	6500
HFC-125	2800	C_2F_6	9200
HFC-134a	1300	SF_6	23900

city owing to the statistical data being relatively complete on this scale. As mentioned above, the GHG emission inventory for the whole city needs to be scaled down to guide GHG emission mitigation actions on the scale within the city, which often lacks enough statistical data for detailed estimation of GHG emissions from different sectors. To address this challenge, we need to develop new methods that do not merely depend on statistical data. As for research on integrating GHG emission into urban planning, many scholars have studied the relationship between urban form and carbon emission or climate change (Davoudi and Sturzaker, 2017; Fang et al., 2015; Lee and Lee, 2014; Xia et al., 2017; Ye et al., 2015) and urban planning strategies or tools for climate adaption or mitigation (Bulkeley et al., 2009a,b; Condon et al., 2009; Davoudi et al., 2009; Hamin and Gurran, 2009; Wamsler et al., 2013). However, few researches have integrated GHG emission inventorying into urban planning to gain the comprehensive understanding of spatial pattern and source control of urban GHG emission. Therefore, it is important to bridge sector to space, i.e. the sectoral GHG emission inventory to spatial pattern designed by urban planning.

As the type and intensity of land use reflects the type and intensity of human activity that in turn determines the type and intensity of GHG emissions, researchers have tried to study the spatial distribution of GHG emissions or energy use within the city using geographic information systems (Christen, 2014; Gurney et al., 2012; Guttikunda and Calori, 2013; Ma and Cheng, 2016; VandeWeghe and Kennedy, 2007). For example, VandeWeghe and Kennedy (2007) conducted a spatial analysis of residential GHG emissions for census tracts in the Toronto Census Metropolitan Area. Gurney et al. (2012) quantified fossil-fuel CO_2 emissions on the building/street scale for the large United States city of Indianapolis. Guttikunda and Calori (2013) presented an emission inventory based on a geographic information system at a spatial resolution of 1 km × 1 km for air pollution analysis (including the analysis of some GHGs) in Delhi, India. Ma and Chen (2016) estimated

Table 2
GHG emission inventory data.

Inventory category (10^4t)	GHG	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6
Energy activities	1631.74	1624.12	4.22	6.93×10^{-2}	1.44×10^{-6}	8.51×10^{-6}	2.10×10^{-7}
Agricultural industry	20.16	20.16					
Manufacturing industy	796.24	796.24					
Steel & iron	34.44	34.44					
Color metal	26.90	26.90					
Chemistry	308.07	308.07					
Construction material	69.03	69.03					
Other sectors	357.80	357.80					
Construction industry	81.30	81.30					
Transportation	331.77	324.15	2.63×10^{-2}	2.28×10^{-2}			
Service industry	197.18	197.18					
Resident	205.09	205.09					
Industrial production process	8.09				1.44×10^{-6}	8.51×10^{-6}	2.01×10^{-7}
Agricultural production process	24.74		5.74×10^{-1}	4.09×10^{-2}			
Land use conversion and forestry	−34.36	−34.36					
Waste disposal	83.12						
Solid waste disposal	75.35	5.50	3.3262				
Residential waste water disposal	7.77		2.97×10^{-1}	4.98×10^{-3}			
Industrial waste water disposal	14.49		5.53×10^{-1}	9.28×10^{-3}			
International transport	25.07						
International aviation	5.55	5.50	3.85×10^{-5}	1.54×10^{-4}			
International bunker	19.52	19.33	1.75×10^{-3}	5.00×10^{-4}			

Table 3
Codes and names of land use classifications.

Code	Class Name
010	Arable land
020	Garden land
030	Wood land
040	Grassland
061	Manufacturing industry land
063	Warehouse land
071	Urban Residential land
072	Rural Residential land
080	Public administration and service land
083	Culture, education sport and health care land
086	Public facility land
087	Park and green space
101	Railway land
103	Street land
105	Airport land
106	harbor and port land

the intensity of building energy use on an urban scale by integrating a geographic information system and big data technology. However, these bottom-up studies included only specific sectors such as residents or buildings, and did not bridge to the GHG emission inventory to guide comprehensive GHG management.

Therefore, to scale down the inventory for the whole city and to bridge the inventory to land use, we develop a framework for the spatial apportionment of a GHG emission inventory and conduct a case study to demonstrate the use of the apportionment framework where we recognize the relationships between the GHG emission inventory and land-use classification. We then visualize the spatial apportionment results by using geographic information system and discuss its practical implications for low-carbon urban planning.

2. Material and methods

2.1. Study area

Xiamen, also known as Amoy, is a city located in the southeast of the province of Fujian in China (24°23′–24°54′N, 117°53′–118°26′E) and has a land area of 1545 km^2 and sea area of 390 km^2. In 2015, Xiamen had a regular population of 3.86 million including an urban population of 3.43 million and a gross domestic product per capita of 14,510 US dollars. The proportions of primary, secondary and tertiary industries were 0.7%, 43.5% and 55.8% in 2015. As a famous tourism city in China, Xiamen attracted 60.36 million (person-times) tourists in 2015. As one of the four earliest special economic zones of China established in 1980, Xiamen has undergone rapid urbanization. During the 35 years since the special economic zone was established, the urbanization rate increased steadily from 35.03% in 1980–88.86% in 2015. Xiamen was selected as one of the eight national low-carbon pilot cities by the National Development and Reform Commission of China in 2010.

As one of 15 sub-provincial cities, Xiamen comprises six administrative districts, which are Siming and Huli on Xiamen Island and Haicang, Jimei, Tong'an and Xiang'an on the mainland (see Fig. 1). The primary functions of Siming and Huli include administration, business finance, tourism and port logistics. Haicang's primary function is secondary industry. The district of Jimei comprises the areas of Xinglin and Jimei, which have primary functions of industry and education respectively. Tong'an established a comprehensive city development goal, which encompasses trade, industry and tourism. Xiang'an unified industry, trade, education, tourism and port logistics as its main development goals.

2.2. Material

As a pilot task, according to *Guidelines for National Greenhouse Gas Inventories* published by the Intergovernmental Panel on Climate Change in 2006 and *Guidelines for Provincial Greenhouse Gas Inventories* published by the National Development and Reform Commission of China in 2011, Xiamen has compiled GHG emission inventories from 2005 to the base year of 2010 to analyze emission sources, the contributions of impact factors and future emissions. The scope of these inventories is illustrated in Fig. 2.

Each inventory has five sectors: energy, industrial processes and product uses, agriculture, forestry and land-use change, and waste treatment. Six GHGs covered by the Tokyo Protocol were assessed: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs including HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea and HFC-236fa), perfluorocarbons (PFCs including CF_4 and C_2F_6) and sulfur hexafluoride (SF_6). All these gases were converted to the CO_2 equivalent according to the global warming potential provided in the *Second Assessment Report on Climate*

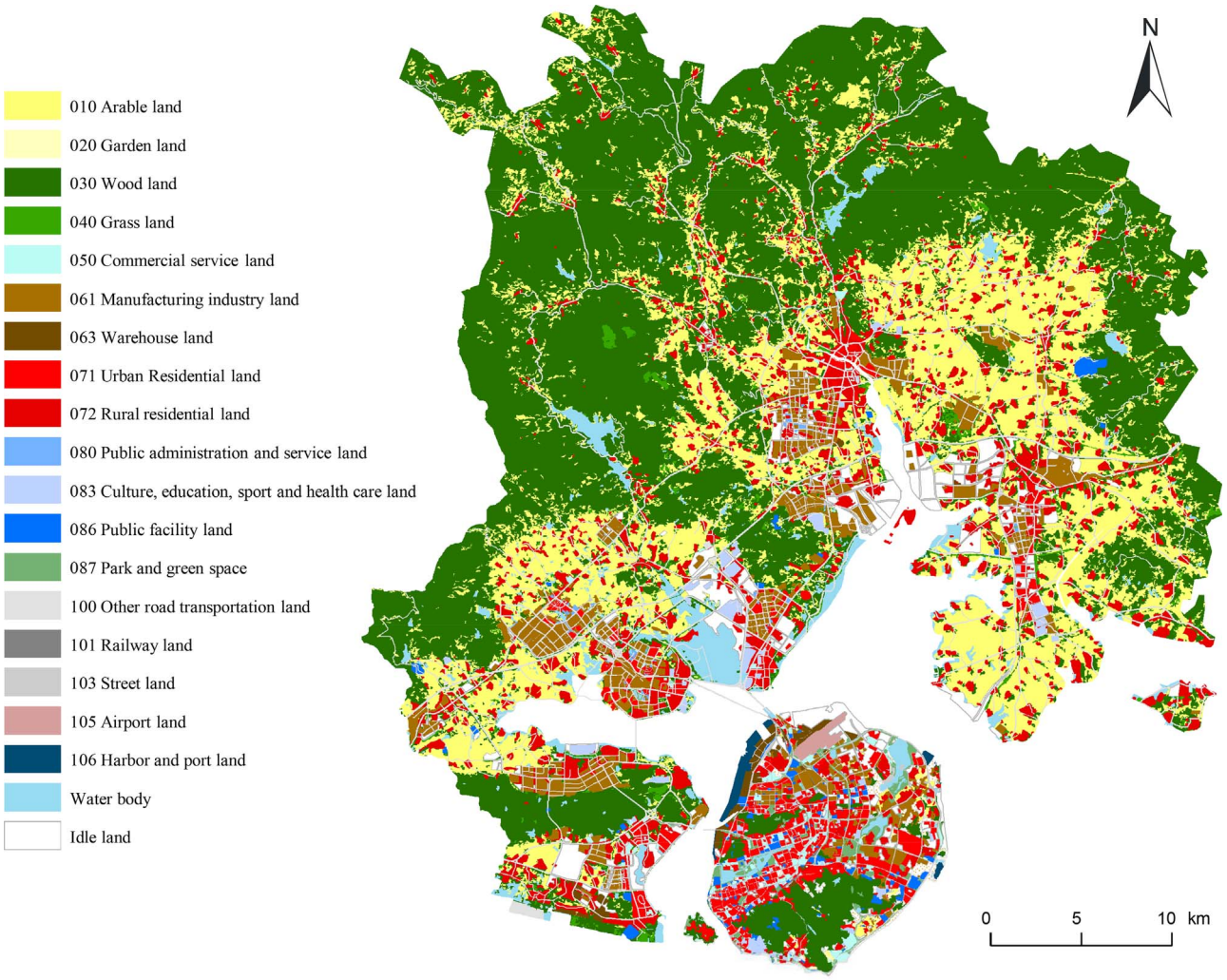

Fig. 3. Land-use types in Xiamen.

Change published by the Intergovernmental Panel on Climate Change (see Table 1). The present study extracted the CO_2 equivalent data of GHG sectors from the inventory report of the base year provided by the Development and Reform Commission of Xiamen. The eventual GHG emission inventory data for this study were shown in Table 2.

For land-use data, we need not only data for the non-built-up area but also data for the built-up area divided by different functions such as residential, industry, commerce and transportation that correspond to the inventory items. Land-use data were therefore collected from multiple sources including integrated remote-sensing imagery such as IKONOS imagery, digitalized land-use maps of urban planning and vector data from the local land-use management bureau (Xiamen Municipal Bureau of Land, Resources and Housing Administration). These sources of data were adjusted to the same coordinate and classification systems; i.e., *Current Land Use Classification Standard* published by the Ministry of Land and Resources of China in 2007. Codes and names of land-use classifications are given in Table 3 and Fig. 3.

2.3. Methods

2.3.1. Basic procedures

The procedures of spatial apportionment are illustrated in Fig. 4. The final aim is to allocate the emission amounts of GHG emission inventory items to land parcels. The important step is to construct relationships between GHG emission inventory items and land-use types. An urban GHG emission inventory should be complied first. Emission items should be made as specific as possible to satisfy the requirements of subsequent spatial apportionment.

Land-use data are required to conduct the apportionment. As the GHG emission inventory items are divided by different sectors, such as the residential sector and industrial sector, the land-use data should be fine enough to include construction land-use types such as residential land, industrial land or transportation land.

The corresponding relationships between GHG emission inventory items and land-use classifications can be constructed using the inventory and land-use data. Four types of relationships and the corresponding allocation methods are summarized in Table 4. The amounts of GHG emission inventory items can be classified, united and reallocated to land use according to the corresponding relationships. In the case of the one-to-one relationship, GHG emission inventory items can be allocated to corresponding land-use types directly; for the other three types of relationships, according to the analysis requirements and conditions of the emission inventory and land-use data, different methods can be used to classify, unite and reallocate GHG emissions items and land-use types. By summing emission items or uniting land-use types, these multiple-correspondence relationships are eventually converted to one-to-one relationships.

2.3.2. Spatial apportionment framework

According to the following responsible relationships: 1) agricultural land is responsible for agriculture fuel combustion activity and agriculture process in GHG emission inventory categories, 2) industrial land

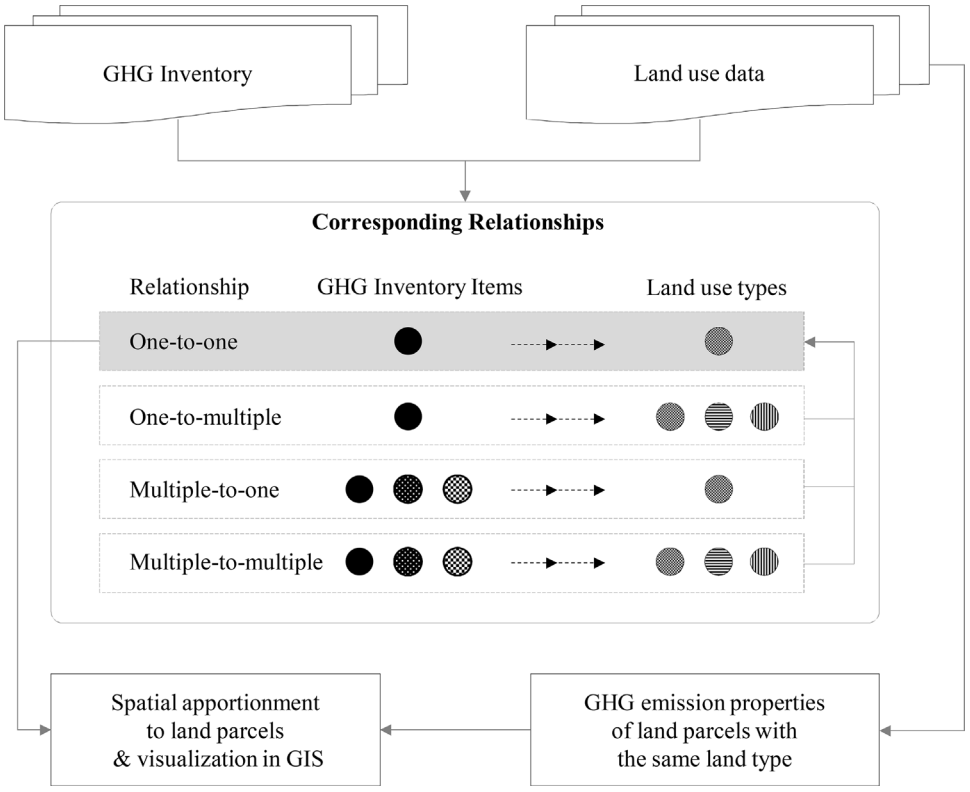

Fig. 4. Spatial apportionment procedures.

Table 4
Corresponding relationships for greenhouse gas emission inventory item and land use.

inventory items	corresponding land use types	allocation methods
one	one	directly allocate to the corresponding land use type
one	multiple	1. estimate the GHG emission intensities of different corresponding land use types 2. allocate to the corresponding land use type according the estimated intensities
multiple	one	1. sum up amount of inventory items 2. allocate the summed amount to the corresponding land use type
multiple	multiple	1. sum up amount of inventory items 2. estimate the GHG emission intensities of different corresponding land use types 3. allocate the summed amount to the corresponding land use type according the estimated intensities

is responsible for manufacturing industry energy activity, industry process and industry waste water disposal GHG emission, 3) residential land is responsible for residential energy activity, residential waste water and solid waste GHG emission, 4) service industry land is responsible for service industry GHG emission; transportation land is responsible for transport energy activity and international transport, 5) wood land and grass land are responsible for land use conversion and forestry, and so on, the framework of the spatial apportionment of the GHG emission inventory for the case city was developed as shown in Fig. 5 based on the spatial apportionment procedure. Therefore, The quantities of these GHG items were summed and allocated to the corresponding land-use type. For example, the agriculture-related GHG inventory items including agriculture fuel combustion and agricultural processes were assigned to agricultural land, industry-related GHG items including industrial fuel combustion, industry processes and industry wastewater treatment were assigned to industrial land, and residential fuel combustion, solid-waste treatment and residential wastewater treatment GHGs were apportioned to residential land. GHGs from transportation, the service industry and land-use change and forest were directly apportioned to transportation land, service industry land and forest and grassland. Because construction may be associated with industrial, residential, service and transportation land, GHGs from construction were apportioned to these types of land according to their areas and apportionment weights.

According to the apportionment framework, the GHG inventory items were rearranged to correspond to the land-use classification given in Table 4. Because all urban construction land-use types involve construction materials and the construction industry, on the basis of the construction area proportion on different land uses in the base year, we reallocated GHG emissions related to construction as 45% belonging to residential land, 30% belonging to manufacturing, mining and warehouse land, 20% belonging to service industry land and 5% belonging to transportation land.

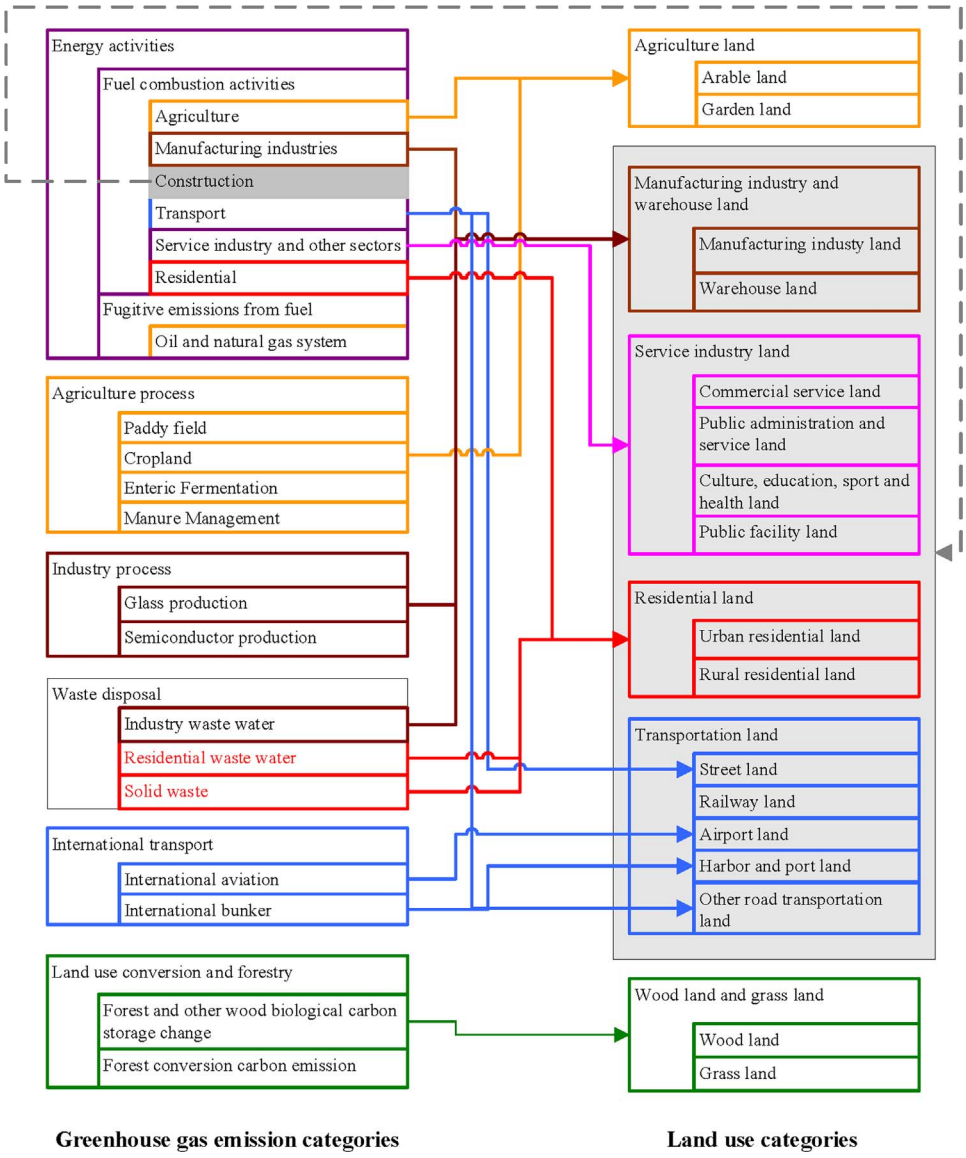

Fig. 5. Framework of the spatial apportionment.

3. Results

3.1. GHG emission intensity of different land use types

The intensity of GHG emissions for each land-use type was obtained by further calculation (Table 5). According to the total amounts of GHG emissions, land-use types can be listed in descending order as manufacturing, mining and warehouse land, transportation land, residential land, service industry land and agricultural land with a ratio of approximately 19:8:7:5:1 if reckoning agricultural land has an emission of 1. For GHG intensity, land use can be listed in descending order as manufacturing, mining and warehouse land, service industry land, transportation land, residential land and agriculture land with a ratio of 89:54:23:14:1 if reckoning agricultural land has a GHG intensity of 1.

The manufacturing, mining and warehouse land had a much greater amount or intensity of GHG emissions than other types of land. The amount of GHG emission from residential land was higher than that from service industry land. However, owing to the large area of residential land, the emission intensity of residential land was less than that of service industry land. Woodland and grassland provided the greatest GHG sequestration but they absorb only low amounts of GHG and far less than the amount of emissions generated by human activities. Additionally, the absorption intensity of woodland was far lower than the emission intensities of other types of land.

3.2. Spatial distribution of urban GHG emission

The spatial distribution of the GHG emission intensity is illustrated in Fig. 6. On the whole, woodland and grassland were the largest areas of GHG sequestration although their intensity of GHG sequestration was very low and they were mainly located in the northwest of Xiamen. For GHG emissions, areas with the lowest emission intensity ($< 0.2 \times 10^4$ CO_2e/km^2), most of which was agricultural land, were mainly concentrated in Xiang'an, northwest of Jimei and northwest of Haicang; areas with the highest emission intensity ($8–16 \times 10^4$ CO_2e/km^2), being disperse from the view of the whole city but being concentrated from the view of each district, were mainly located in the north of Huli, the north of Haicang, the southwest of Jimei and on the both sides of

Table 5
GHG emission inventory categories and the corresponding land-use types for Xiamen.

Inventory category	GHG (10^4 tCO_2e)	Construction reassignment weight	reassigned GHG (10^4 tCO_2e)	Land- use type	Area (km^2)	GHG intensity (10^4t CO_2e/km^2)
Agriculture related	**44.90**	0%	44.90	Agricultural land	334.17	0.1344
Agricultural energy activities	20.16					
Agricultural production process	24.74					
Industry related	**818.82**	30%	843.21	Manufacturing, mining and warehouse land	70.81	11.9081
Industrial energy activities	796.24					
Steel & iron	34.44					
Color metal	26.9					
Chemistry	308.07					
Construction material	69.03					
Other sectors	357.8					
Industrial production process	8.09					
Industrial wastewater disposal	14.49					
Construction industry	**81.3**	−100%	0			
Service industry	**197.18**	20%	213.44	Service industry land	29.47	7.2426
Transportation	**356.84**	5%	360.905	Transportation land	117.45	3.0728
Resident related	**288.21**	45%	324.795	Residential land	165.96	1.9571
Residential energy activities	205.09					
Solid waste disposal	75.35					
Residential waste-water disposal	7.77					
Land-use conversion and forestry	**−34.36**	0%	−34.36	Woodland and grassland	721.33	−0.0476

Tongan Bay in Tong'an and Xiang'an. Areas with emission intensity between 0.2 and 2×10^4 CO_2e/km^2 were mainly distributed in the middle of Xiamen Island, southeast of Jimei and east of Tong'an; areas with emission intensity between 2 and 4×10^4 CO_2e/km^2 were mainly transportation land corresponding to the city's roads and harbor and port land; areas with emission intensity between 4 and 8×10^4 CO_2e/km^2 were relatively small and are not obvious on the map.

3.3. Spatial distribution on district and town scales

According to the spatial apportionment results, the quantity and intensity of emissions of the six districts and different towns of the six districts of Xiamen can be summed according to the administrative boundaries; results are shown in Figs. 7–9.

On the district scale (see Fig. 7), Tong'an had the largest emission quantity and Siming had the smallest quantity. However, the situation for the emission intensity was different in that Tong'an had the lowest emission intensity because it has the largest land area in Xiamen, and Huli had the highest emission intensity because of its smallest area. Siming has the second largest land area in Xiamen and had the second highest emission intensity.

On the town scale (see Figs. 8 and 9), towns with emission quantity less than 35×10^4 CO_2e were in the northwest of Jimei District and Tong'an District and in the southeast of Xiamen Island. Diqian in Huli District, Xinyang and Haicang in Haicang District, Guankou in Jimei District, Ximin and Xike in Tong'an District and Maxiang in Xiang'an District had the quantities more than 70×10^4 CO_2e, which had most of manufacturing industry land and warehouse land of each district (see Fig. 6). The situation for the emission intensity was also different from quantity on the town scale. Most of the towns with intensity more than 2×10^4 CO_2e/km^2 were located in the north of Xiamen Island and along Tong'an Bay in Tong'an District.

Overall, the vast majority of agricultural land for GHG sequestration was located outside of Xiamen Island, contiguous to woodland and grassland in the peripheral area of the city. Most land-use types in the central region of Xiamen had high GHG emissions. It is expected that, with the expansion of the city, agricultural land, woodland and grassland with low GHG emissions will be replaced by construction land with high GHG emissions. It is therefore necessary to conduct more scientific and reasonable urban planning for Xiamen.

4. Discussion and policy implication for urban planning

Different from previous study, which mainly focused on inventorying GHG emissions (Lin et al., 2013; Lin et al., 2014; Lin et al., 2016), this study attempted to bridge the sectoral GHG emissions to spatial land use. Contrast to GHG emission inventory on a city scale, the results can be spatially visualized and summarized on different scales such as district or subdistrict, which can provide directly perceived information for GHG emission control and management. Meanwhile the sector-based and comprehensive characteristics of GHG emission inventory can provide emission source control and comprehensive understanding for urban planning, which could not directly obtained by the study that estimated some types of emission by physical models (Guttikunda and Calori, 2013; Polson et al., 2011).

Urban planning can integrate GHG reduction strategies from an urban spatial structure strategy and an urban spatial connection strategy. The structure strategy is mainly based on land-use proportion adjustment. It will reduce spaces with high GHG emissions and increase spaces with low GHG emissions or negative GHG emissions; i.e., spaces providing GHG sequestration. Generally, there are two ways of reducing high-emission spaces. One is altering the function of the high-emission space with the low-emission land use. The other is increasing the utilization efficiency of a high-emission space.

Transportation connects function zones in the urban area and transportation connections vary owing to the different arrangements of urban functional zones. The connection strategy is to avoid unnecessary traffic and high-emission transportation such as the use of private cars.

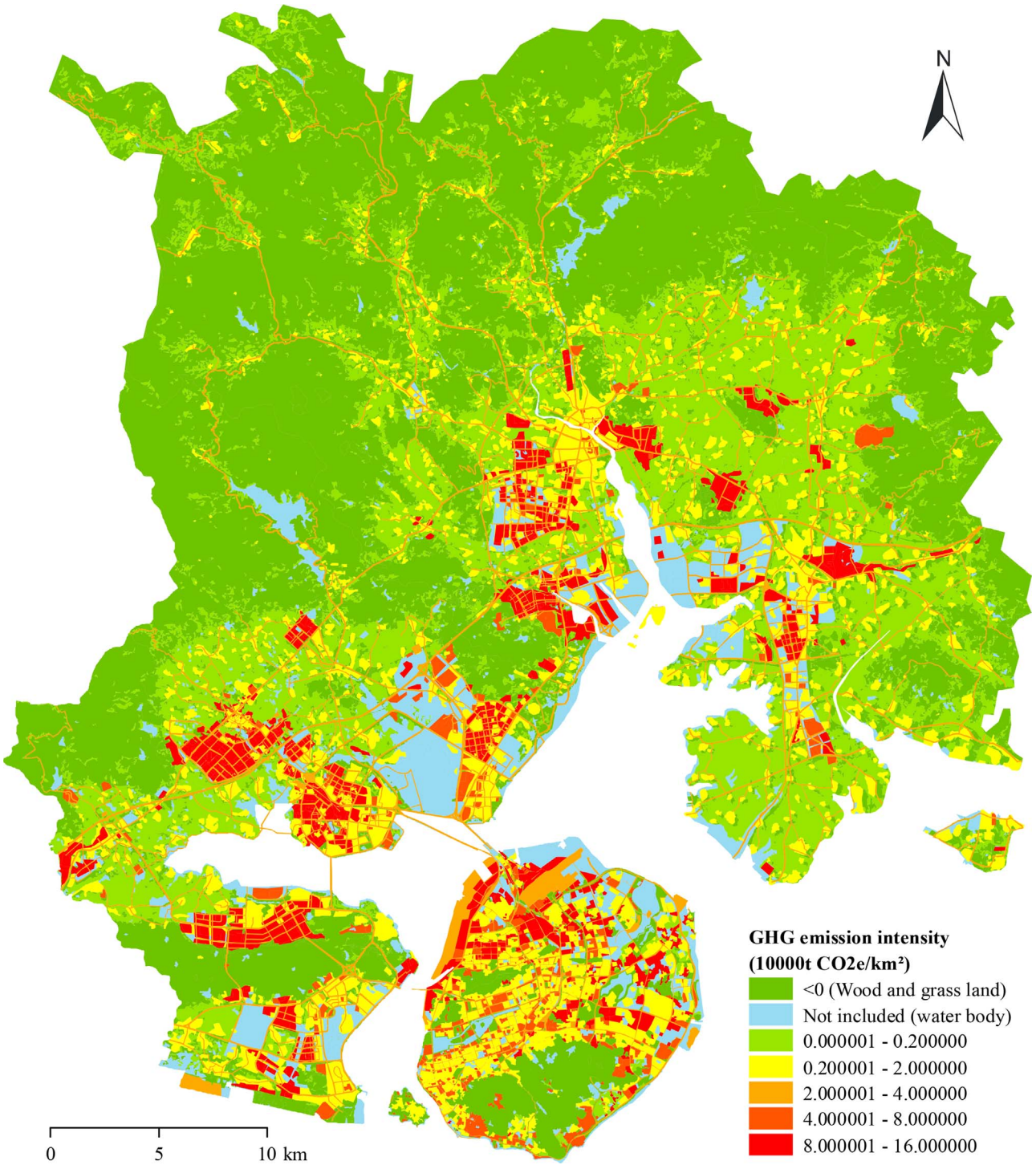

Fig. 6. GHG emission intensity distribution.

There are two ways of realizing the connection strategy: size control and function balancing.

4.1. Structure strategies

Because a construction space has higher GHG emission intensity, more effort should be put into the reasonable management and control of city construction spaces, especially industrial parks. With the support of land suitability analysis and GHG emission prediction, to coordinate economic development and ecological conservation, abundant land space should be reserved for economic development and city construction while guaranteeing ecological security. Considering the GHG emission intensity, firstly, the space can be divided into two types of area, the negative GHG emission area and the positive GHG emission area. Then the positive GHG emission area can be divided into three types of area, the low, medium and high GHG control area. So finally the whole city space can be divided into four types of regulation area, and different carbon control measurements should be taken for each type of area according to its spatial characteristics of GHG emission, which were shown in Table 6 and Fig. 10.

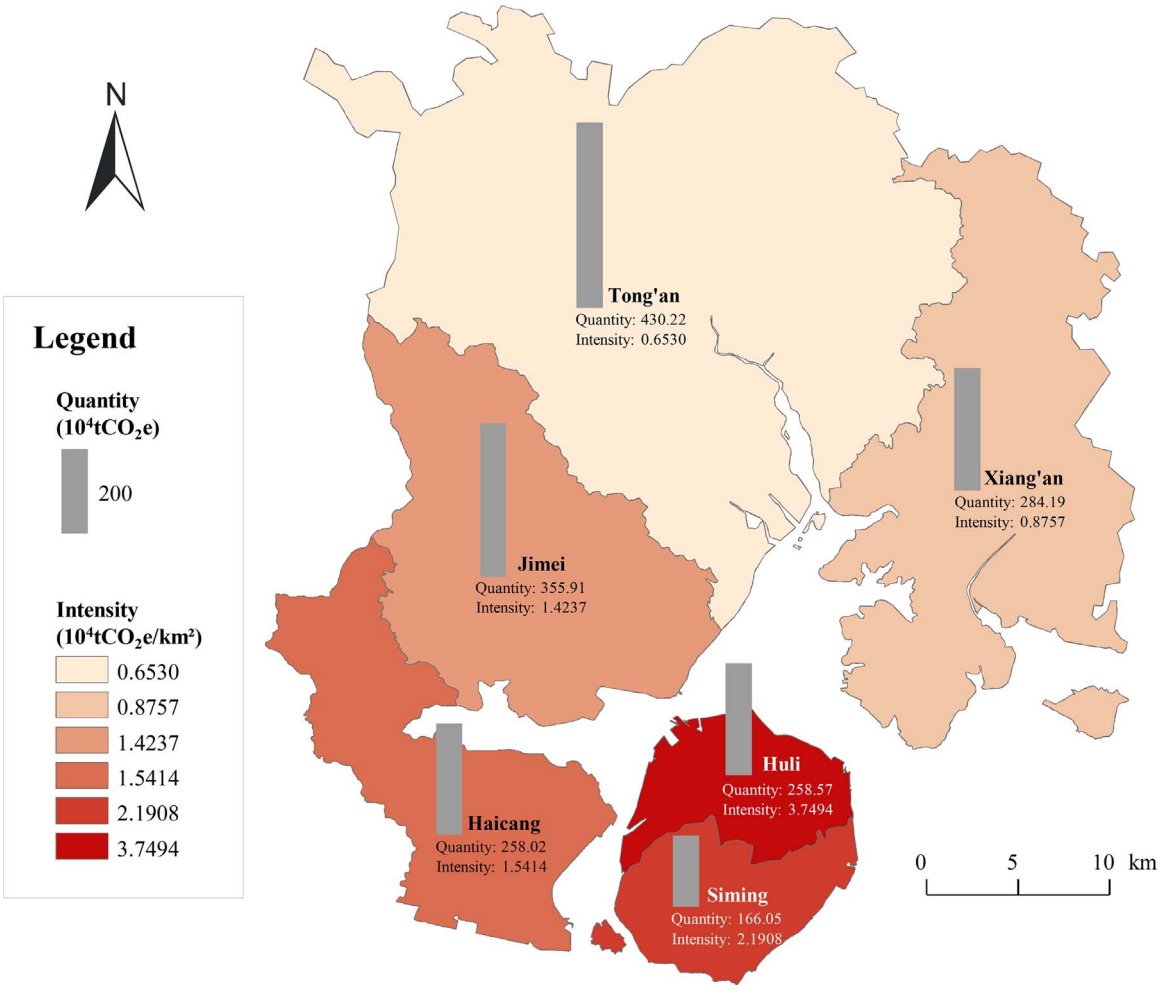

Fig. 7. GHG emissions by district.

As a high-emission space cannot be replaced with a low-emission space completely, we also need to promote the *efficiency* of a high-emission space. Flexible renovation is suggested for an old residential area and urban village most of which were located inside the Xiamen Island; this renovation mainly relies on subsidy encouragement and comprehensive regulation. Conservation measures should be adopted for historical areas in Siming District and Tong'an District to avoid the destruction of historical buildings. Low-carbon ecological techniques should be adopted to realize resource cycling in urban renovation. Meanwhile, industry that has been relocated from Xiamen Island should alter its functions from traditional manufacturing to tourism or creative industries. More efforts should be put in promoting the use of three-dimensional spaces, synthesizing transportation systems, and constructing underground commercial areas to enhance utilization efficiency of land resources.

4.2. Connection strategies

On the city scale, the disordered sprawl of construction land that may increase long-distance commuting should be avoided. Xiamen is now undergoing a process to shift urban functions from the inside to the outside of the Island, which needs low-carbon spatial structure planning to comply with the demands of social economic development, energy conservation, emission reduction, industrial clustering and environmental conservation, to guide and regulate spatial planning, to refine the spatial layout of industrial clusters, to strengthen ecological control-line management and to control the boundary of city growth. Establishing a green space in the shape of a ring, belt or wedge in the northwest of the city which are dominated by forest and mountains as shown in Fig. 3, can strengthen the ecological barrier among clusters and maintain the integrity and continuation of the urban structure to avoid disordered sprawl.

On the land parcel scale, maintaining a suitable parcel size and development intensity and revising road construction standards can make the block size and road density favor non-motorized vehicle traffic and public transportation. The parcel size should vary in accordance with the distance from the parcel to the city center. Parcels close to the city centers, which include the main city center in Xiamen Island and four sub-city centers in Haicang Subdistrict in Haicang District, Jimei Subdistrict in Jimei District, Datong Subdistrict in Tong'an District and Maxiang Subdistrict in Xiang'an District, should be small to encourage walking and cycling. Thereof, the size should increase as the distance to the city centers increases.

For Xiamen City, the challenges to balance the spatial layout of urban functions come from the professional industry zones in the four districts outsides the Island, which lack residential public services for

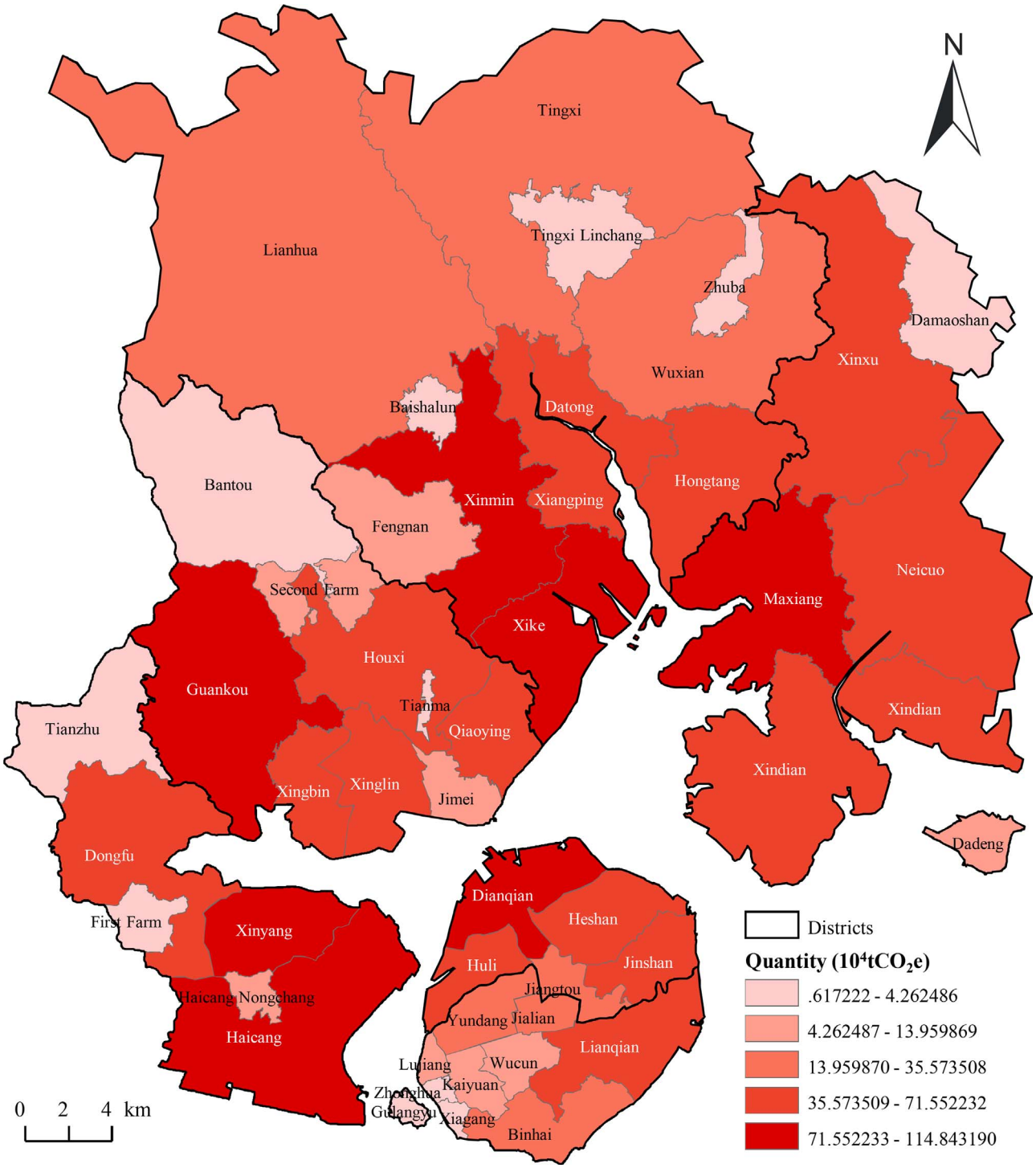

Fig. 8. GHG emission quantities by town.

industry workers and managers. Methods of balancing the spatial layout of these professional industrial zones include (a) avoiding absolute function zoning and a single function for one large area (i.e., improving the commerce–housing balance by mixing residential land use and service sector land use and partially secondary industry land use, and mixing horizontal land use and vertical land use) and (b) reducing the commute distance by adopting an efficient mix of land uses.

5. Conclusions

In this paper, we tried to bridge the urban GHG emission inventory for climate change mitigation to land-use classification for urban planning, and proposed a framework for the spatial apportionment of an urban GHG emission inventory. Xiamen was taken as a case study to demonstrate the framework of spatial apportionment. The results clarified the spatial distribution of GHG emissions for Xiamen and its six administrative districts. The vast majority of land for GHG sequestration was located in the peripheral area of the city. Most land-use types

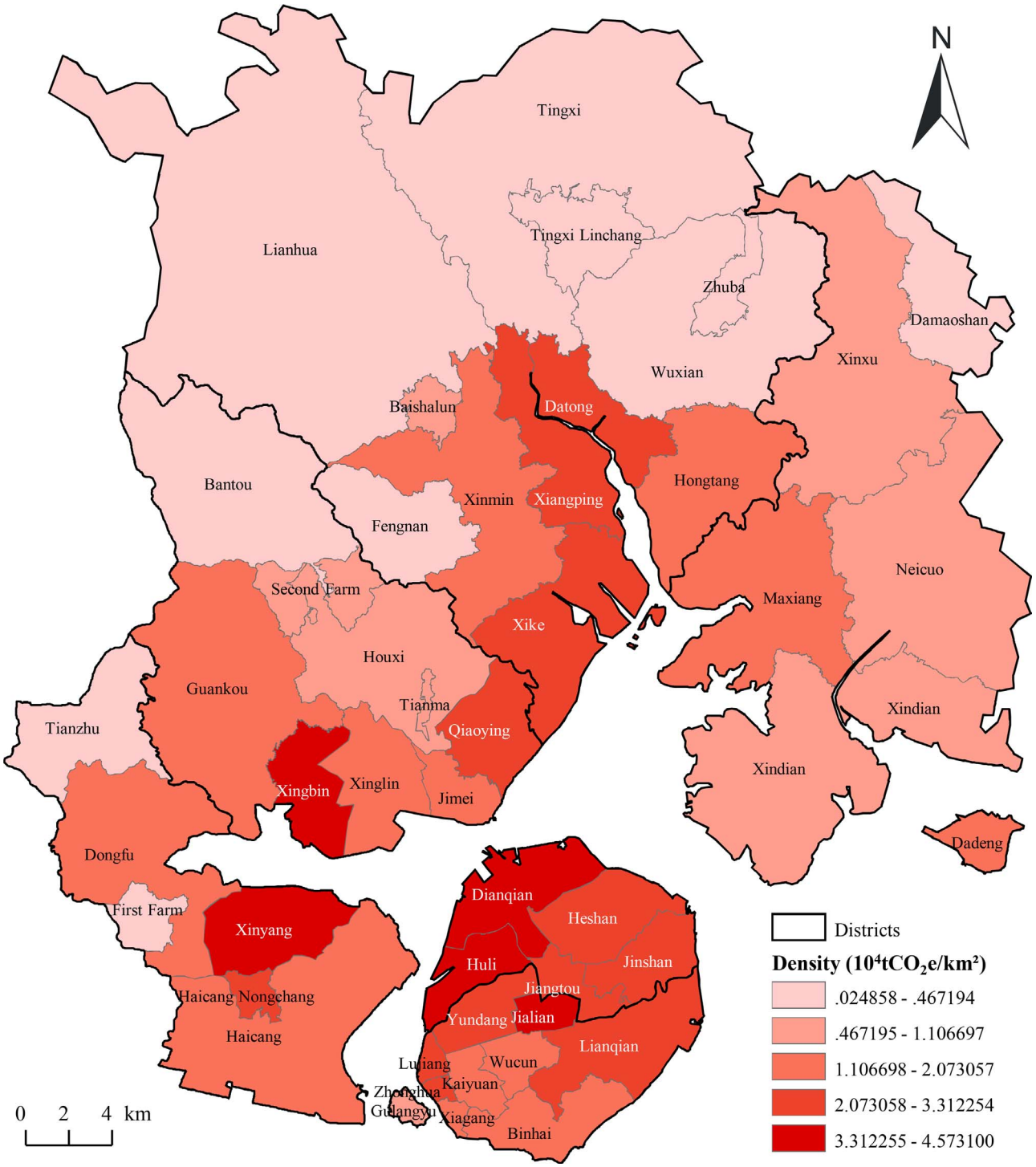

Fig. 9. GHG emission densities by town.

in the central region of Xiamen had high GHG emissions. With expansion of the city, land-use types with low GHG emissions are expected to be replaced by land-use types with high GHG emission. It is thus necessary to conduct urban planning for Xiamen that is more scientific and reasonable. The implications for low-carbon urban planning were discussed in terms of structure and connection strategies which included regulating the urban GHG emission space, promoting the efficiency of high-emission spaces, controlling the spatial size of the city and balancing the spatial layout of urban functional zones. Integrated with socioeconomic factors and the urban land-use distribution, the spatial apportionment of GHG emissions allows an analysis that is more accurate for tracing emission sources and better for managing emission sources through urban planning.

However, as we just demonstrated the preliminary application of the spatial apportionment method, there are great rooms to improve in the future, especially for different cities. Further studies can estimate the GHG emissions from land parcels with the same land use type according to their different land use properties, such as building area, population, production and other relevant factors. On the basis of the results from the spatial apportionment procedures, according to a further survey of emission properties of land parcels of the same land-use type, the allocation proportion can be determined and emission items

Table 6
Spatial management and control of GHG emissions.

Regulation area	including land space	carbon control measurement
GHG sequestrations protection area	Forest, grassland, park and green space	Aiming at zero emissions, strict control on GHG emissions
Low GHG strict control area	Farmland, orchard, contiguous rural residential area	Strict control on GHG emissions according to low GHG standard
Medium GHG moderate control area	Xiamen island, and urban area of four districts off the island	Reducing GHG emissions by energy conservation techniques and management measures
High GHG reduction area	Industrial parks in four districts off the island	Enhancing energy resources and land utilization efficiency at maximum level, promoting circular economy and cleaner production, and establishing low GHG industry demonstration zone

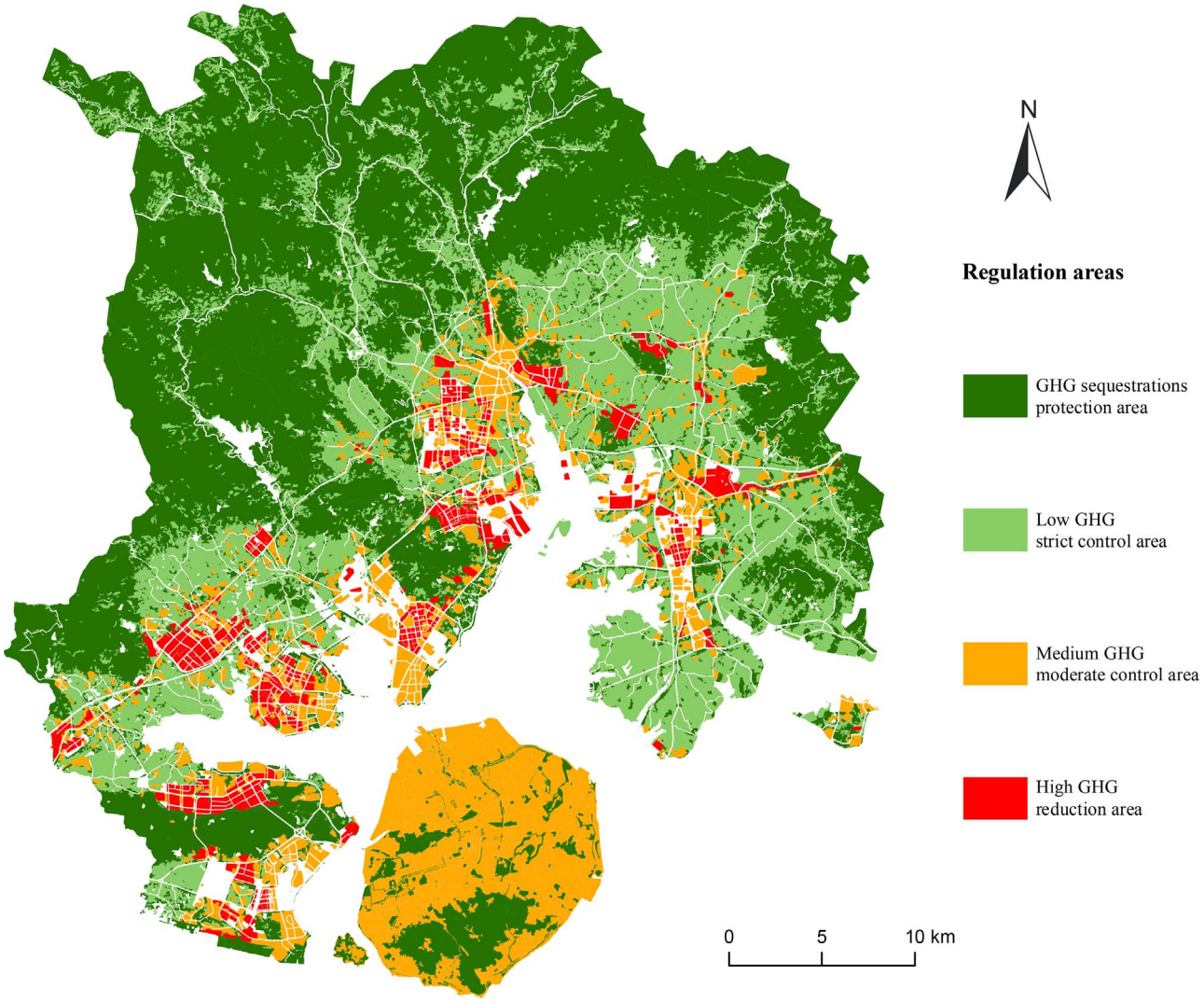

Fig. 10. Regulation areas of GHG emissions.

reallocated to land parcels. For example, emissions from residential land, transportation land and manufacturing industry land can be reallocated according to population, traffic flow and production in each land parcels respectively. Moreover, for the spatial apportionment and the further estimation, we need validation from other research methods such as field investigation and remote sensing retrieval. All these further studies will provide scientific support for more reasonable management and planning for GHGs mitigation actions.

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